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ES&H Section

RP. NOTE 140

Dose Attenuation Methodology for NuMI Labyrinth, Penetrations and Tunnels

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I. Introduction

This note describes the methodology used to calculate the radiation attenuation factors for the NuMI labyrinths and penetrations. The calculations start with the Radiation Physics note 118[1] (RP118), which provides a spreadsheet for calculating radiation dose attenuation along human-size labyrinths with 90 degrees bending legs. Using the source term and the attenuations parameterized in RP118, this note describes extensions to spreadsheet, using simple analytical arguments, to calculate variations to standard situations. RP118 should be referenced for the detailed description of the source term and the parameterization of the experimental attenuation curves.

This note describes how situations such as the penetrations, labyrinths with legs at varying angles to each other (including collinear), large tunnels, point sources, line sources, off-axis sources, anisotropic distribution of the source and dose attenuation at the exit are treated. A very simple-minded radiation leakage through the shield around the first leg is also considered.

II, Source Term

A few features were added to the point source term. Line source and off-axis source options have also been added.

Anisotropic Point Source

In RP Note118 the source term is isotropic, or assumes that the first leg is at 90 degrees to the beam direction and the other legs are at 90 degrees to each other. Sullivan[2] has parameterized the secondary particle yields as a function of the beam energy and the zenith angle. It is assumed that the source has azimuthal symmetry. Figure 1 shows the definition of the Sullivan angle θ_S. To remain consistent with RP118, the Sullivan yield at 90 degrees has been normalized to the RP118 source term. At other angles the ratio of the Sullivan yield to its value at 90 degrees is used to correct the RP118 source term. Figure 2 shows the Sullivan correction factor for different energies and angles.

$$\textit{Sullivan Correction Factor} = \phi(E,\theta_S) \big/ \phi(E,90^\circ)$$

The source location with respect to the opening is determined by three parameters; height of the opening above the beam line, transverse offset and longitudinal offset from the direction of the opening surface (see Fig.3). Angle θ_S is calculated using these three parameters from the projection in a plane containing the beam direction and a line connecting the source to the center of the opening.

Angle of the First Leg

One of the factors that can easily affect the amount of radiation entering a labyrinth or penetration is the angle that the first leg makes with entrance opening. Figure 1 shows this angle. It is defined to be the angle between the direction of the surface of the opening (which is represented by a unit vector normal to the surface) and the axis of the first leg. This angle is generally zero for the person sized labyrinth, but it could be non-zero for utility penetrations or for unusual passageways. This angle is taken into account by multiplying the source term by the $\cos(\theta_1)$. Cosine of the angle is chosen, mainly because of the definition of the solid angle.

Line Source

Line source strength is calculated using the source length and the planar angle subtended by the source at the center of the opening. The source term ϕ_L is calculated using

$$\phi_L(rem) = \frac{S_L}{4\pi K \cdot R}\vartheta_L$$

Where S_L is the line source strength in neutrons per unit length. θ_L (radians) and R are defined in Fig.3.b. The constant K is $3x10^7$ (neutrons/cm^2/rem), which is the same as that used for the point source[1]. Estimating the realistic line source length requires a good understanding of the beam optics at the loss location, especially for linear machines and beam lines. In the absence of good loss information for circular machines a 1m source length is reasonable.

Plane Source

Even though the calculation of a plane source is simple, guessing the actual planar dimensions is more difficult than it is for the line source. Given that the beam's path is a line, it is generally easier to assume that what seems planar has emanated from a line source. Note also that any parameterized point source approximates a volume source. A plane source at the mouth of the labyrinth, ϕ_{Plane}, can be approximated by a point or line source at some distance. For the cases where there is a true plane source of dimensions L and W, such as an activated beam monitor,

$$\phi_{plane}(rem) = \left(\frac{2S_p}{\pi K}\right)\tan^{-1}\left[\frac{\varepsilon}{\eta\sqrt{\left(1+\varepsilon^2+\eta^2\right)}}\right]$$

Where S_p is the plane source strength in neutrons per unit surface, ε=W/L and η =2R/L. The constant K is the same as that used for the line source

Off-axis Source

Off-axis is described as the condition where radiation/loss source is not on the cylindrical axis of the first leg. This situation is basically correcting the solid angle subtended by the source at the labyrinth opening. The integration of the flux is over the surface, over the direction from which the radiation is coming. The net flow rate is a component of the vector current density with respect to the normal to the surface through which the flow is occurring (see Fig. 4). The current density at the opening is related to flux density by

$$j(\vec{r}_{Source},\vec{\Omega}) = \phi(\vec{r}_{Source},\vec{\Omega}) \cdot \cos\alpha \qquad where \quad \cos\alpha = \vec{n} \cdot \vec{\Omega}$$

Figure 3 describes the three length parameters used to calculate the distance and the angle of the source to the opening. The angle of the first leg, discussed earlier is not independent of the off axis source correction angle. The angle of the first leg is compared with α and is adjusted, to avoid over correction. This correction may be required when the source is longitudinally upstream or downstream of the opening, but the first leg angle located such that it can receive direct components from the source.

III. Methodology –Attenuation Calculations

The input geometric parameters are in English units. However, since the original parameterization is done in metric units, the calculations are carried out in metric to avoid possible inherent systematics imbedded in the parameterization.

Non-ninety Degree Legs

In standard labyrinth methodology, it is assumed that all the legs are at 90 degrees to each other. MARS or Fluka simulations show that an order of magnitude reduction in flux occurs at the right angle turns. However, if legs are at other angles (usually less than 90 degrees) to each other, some of the radiation propagating down the previous tunnel could enter the tunnel without additional scattering or with smaller scattering angles. Dose at the entrance to the new leg will be larger than that for a 90 degree bend. Therefore an angle term of (1+cosθ) has been added based on heuristic arguments. For an angle of 90 degrees, the original formulation is restored. If the new leg has turned 180 degrees around, the term correctly predicts the near cancellation of the attenuations. Therefore, if the attenuation of leg "*i*" is A_i, then

$H_1=H_0A_1(1+\cos\theta_2)$
$H_2=H_1A_2(1+\cos\theta_3)$
…
$H_i=H_{i-1}A_i(1+\cos\theta_{i+1})$

Figure 5 shows the definition of the angles and doses. Note that (1+cosθ) is an approximation to exp(cosθ). However, given the degree of approximations involved, this refinement was not pursued.

Collinear Legs

If the second and further legs of the labyrinth are collinear with the first leg, but could have different lengths and cross sections, their attenuations are calculated using the attenuation parameters for the first leg. Second and following legs are considered collinear if their leg angles (θ_2, θ_3…) are zero. Figure 6 shows an example.

Tunnels as a Special Case

Patterson and Thomas[3] give an approximate expression for the attenuation length, which is a function of the radius of the tunnel. This reference mentions that the expression is valid for radii from 4m to 40m, and that no systematic study has been carried out.

However, given the nature of scattering and radiation transport, it seems feasible to approximate a curved tunnel as a polygon (See Fig.7). In such an approximation the tunnel is replaced with a multi-legged labyrinth. The length of each leg is approximated by starting from the loss point and using straight line-of-sight chords of the curved tunnel. The angle between the legs will be the angle between consecutive lines. Figure 7 shows a circular tunnel, but this approach could be used for any shape or radius. There may be cases where because of the location and magnitude of the loss or the size of the tunnel, it may be necessary to add contributions from both directions.

Penetration and Long Legs of Labyrinths

The attenuation of the labyrinths is generally parameterized in terms of the dimensionless quantity which is the ratio of the length of the leg to the square root of the cross sectional area of the leg. For penetrations and labyrinths with the leg-units larger than 20, most of the radiation coming in the direct line of sight of the source makes it to the end of the leg. Therefore, for the first leg of these long penetrations, simple solid angle attenuation is used:

$$H = H_0 \frac{A\cos\theta_1}{4\pi L_1^2}$$

Where the parameters are defined in Figs. 1 and 5. Note: the solid angle-only method for long legs (leg unit>20) is valid for the first leg and further legs if they are collinear with the first with no intervening bends. The angular divergence of the source for the secondary legs is very large compared to that of the original source; i.e. there are a lot less radiation components that can make it through the leg without any significant scattering. This is why for the second and further legs, the standard calculations can give you a smaller attenuation than the straight solid angle approximation.

Simple Short Circuit

If the first leg of the labyrinth is not long enough, radiation leakage straight through the wall reaching the second leg may be “significant”, when compared to that coming through the first leg. Given the uncertainties associated with the measurements of the universal attenuation curves, “significant” is defined here to be greater than 20% of the radiation coming through the first leg.

When the labyrinth legs are not at right angle to each other, the leakage will vary with the location in the second leg. The composition and thickness of the walls or the fill between the walls and around the labyrinth are not known *a priori* here. Several simplifying assumptions are made to be able to calculate a rough leakage dose to alert the designer. The leakage calculations can be made more exact when a specific design is available.

It was assumed that the wall and the fill to be soil of density 2.24g/cm2. The leakage was then calculated for a point in the middle of the second leg. Figure 8 shows the condition used.

$$d = L_1 + x = L_1 + \frac{L_2}{2}\cos\theta_2$$

$$A_{sc} = 10^{-\frac{d}{\lambda}} \quad and \qquad H_{sc}\left(Dose\right) = H_0 A_{sc}$$

Where d is average thickness of the shield, from loss point to the second leg, λ is the attenuation length through soil and A_{sc} is attenuation of the intervening soil. The dose from leakage (Hsc) is added as a constant offset to the dose in the second leg (see Fig.8 Short-circuit).

$$H'_1 = H_0\left(A_1 + A_{sc}\right) = H_1 + H_{sc}$$
$$H'_2 = H_1 A_2 + H_0 A_{sc} = H_2 + H_{sc}$$

Distance from Exit to 5 mrem/hr Boundary

The dose at a distance from the exit of the tunnel is generally independent of the cross sectional shape of the tunnel at the exit. To avoid increasing the number of input parameters for this calculation, a circular exit opening is assumed, with the area equivalent to that of the exit opening. Since, some times the area around the exit may or could not be restricted, the distance from the exit to the boundary (ropes, fences, walls, or doors) may be comparable to the effective radius of the cross section of the exit opening. Comparison of the exact and approximate attenuation calculations show up to 30% underestimation by the approximate method. Therefore, exact rather than approximate attenuation is calculated[4].

References

1. Don Cossairt "Approximate Technique for Estimating Labyrinth Attenuation of Accelerator Produced Neutrons", RP. 118, September 1995.

2. A. H. Sullivan, "The intensity distribution of secondary particles produced in high energy proton interactions", Rad. Prot. Dos. 27 (1989) 189-192.

3. H. W. Patterson and R. H. Thomas, *Accelerator health physics* (Academic Press, New York, 1973.).

4. J. D. Cossairt, "Radiation physics for personnel and environmental protection", Fermilab Report TM 1834, Section 5.2.6. February 2003.

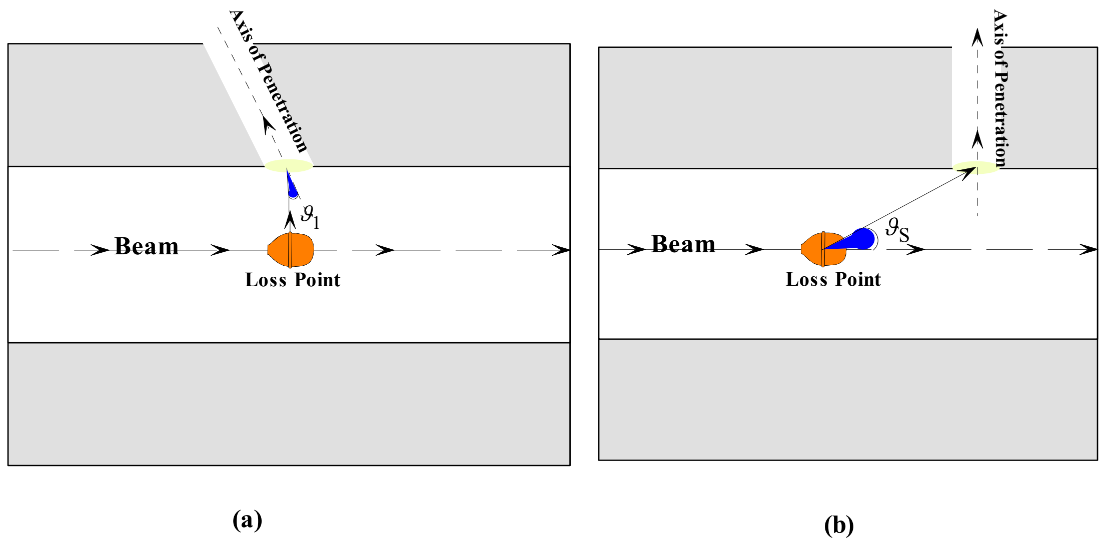

Figure 1. Schematic diagram showing (a) the definition of the $\boldsymbol{\theta}_1$, the entrance angle to the first leg, (b) the definition of the Sullivan angle. Source distribution (loss point) is shown to be asymmetric.

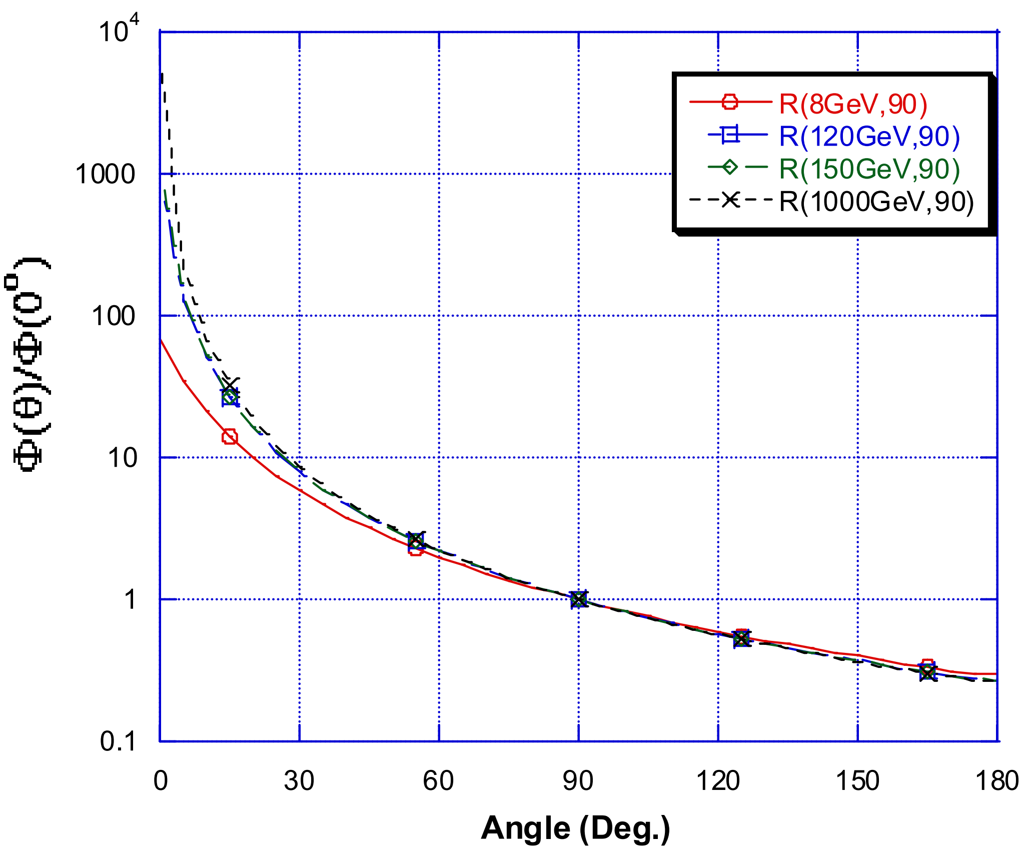

Figure 2. Sullivan Correction factor normalized to the 90 degrees value, for different energies and angles.

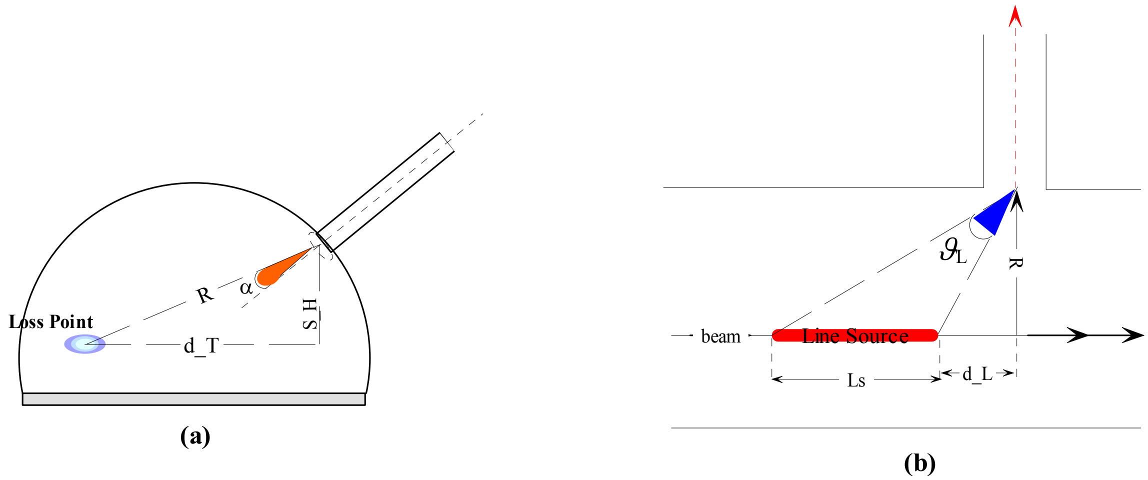

Figure 3. Schematic representations showing the definitions of the some of the input source parameters; source height (S_H), transverse offset (d_T), longitudinal offset (d_L), and the line source length (Ls). The other shown parameters are calculated.

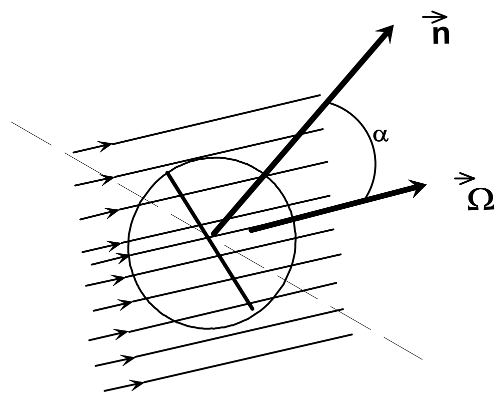

Figure 4. Relation between vector current density to flow rate across a unit area. Vector Ω shows the direction of the flux and the vector n is the direction of the surface.

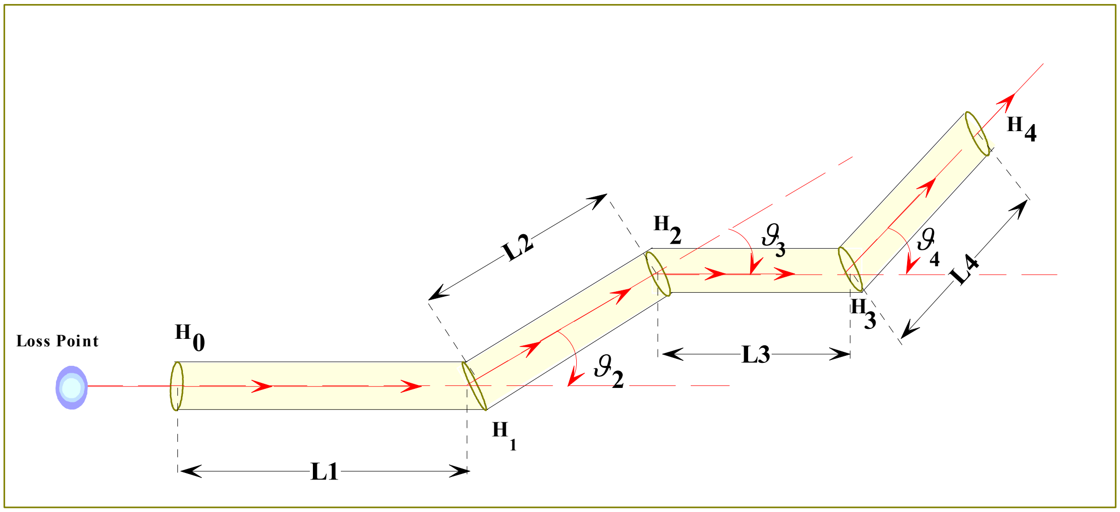

Figure 5. An example diagram of a multi-legged labyrinth where the legs are at different angles to each other. The "H"s are the dose rate at the entrance to each leg. "L"s are the lengths of the legs, "**θ**"s are angles that each leg makes with the previous one. Not shown are the cross sections of each leg, which can be different and a non-zero $\boldsymbol{\theta}_1$.

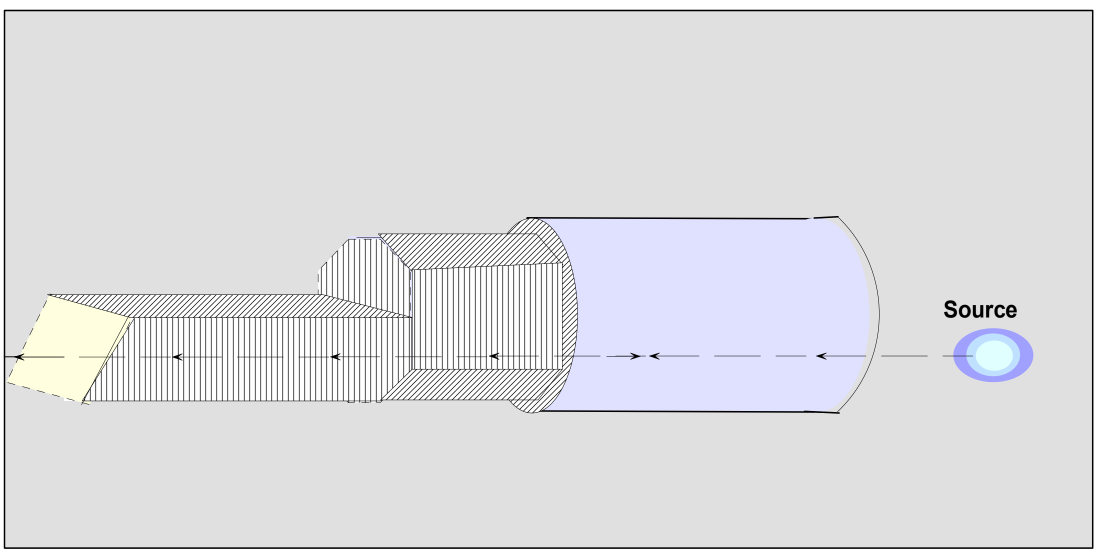

Figure 6. An example of a labyrinth where the first three legs are collinear.

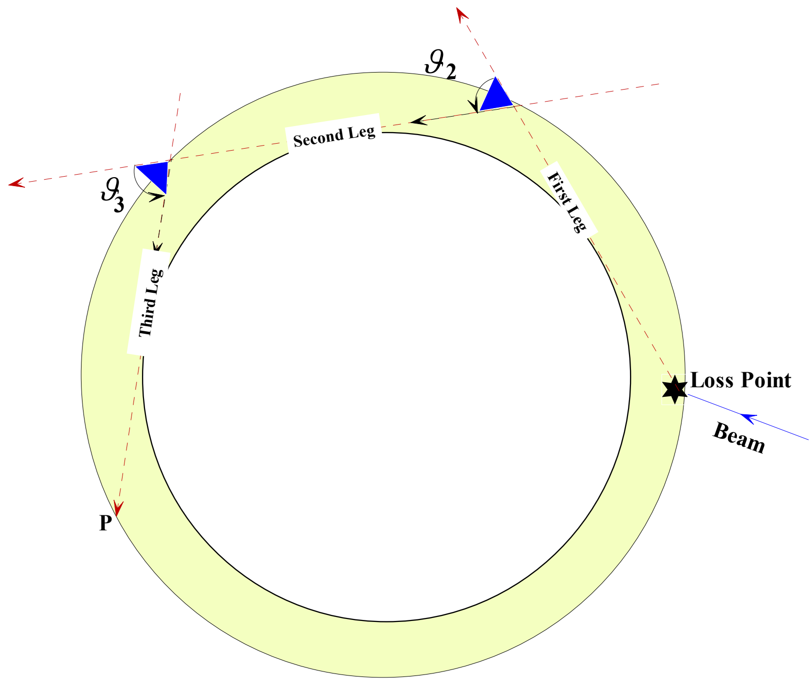

Figure 7. Schematic diagram showing how a curved tunnel can be approximated by a polygon. For this approximation $\mathbf{\Theta_1}$ is zero.

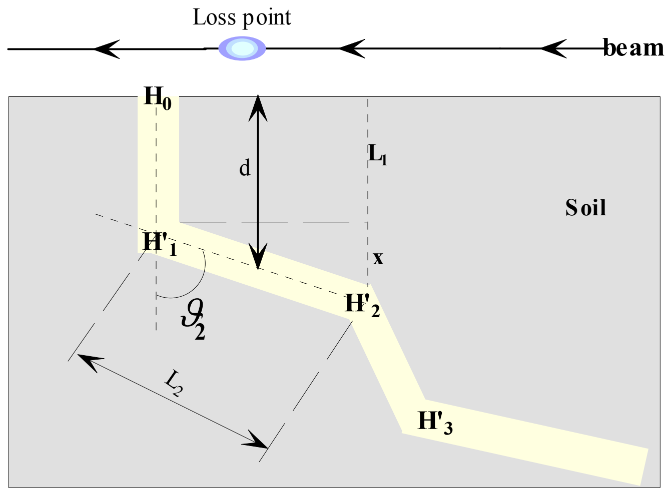

Figure 8. Schematic showing the contribution of radiation leakage to the dose in the second leg and further legs.